

# Monolithically-Integrated 3D RF Filtering Technologies Enabled by Nested Resonator Arrays and Multi-Material 3D Printing (NERON)

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**Abstract**— In this report, new classes of monolithically-integrated, highly-miniaturized three-dimensional (3D) RF filtering technologies are presented for next-generation 6G wireless communication systems. By exploiting the free-form capabilities of additive manufacturing (AM), this project introduces compact dual-channel filters based on a novel high-Q nested ridge waveguide (RW) resonator that provides two fully isolated and independently reconfigurable fundamental modes within a single resonator. Size compactness is achieved by: 1) re-using traditionally unused areas of a RW resonator and 2) monolithic integration enabled by stereolithography apparatus (SLA)-based 3D printing. Further improvements in miniaturization, channel selectivity, and spectral coverage are achieved by using nested waveguide resonator arrays to realize widely spaced, closely spaced, or co-located filtering channels, achieving up to 116 dB inter-channel isolation. Furthermore, the potential of a two-material piezo drop-on-demand inkjet printing process is also explored and exploited to realize 3D self-packaged waveguide (WG) bandpass filter (BPF). It exhibits a 3D waveguide BPF with an ultra-compact volume of  $0.34\lambda_0 \times 1.26\lambda_0 \times 0.16\lambda_0$  and infinitesimal weight of  $< 1.2$  g.

**Index Terms**—additive manufacturing, bandpass filter, dual-channel filter, inkjet printing, monolithic integration, piezo jetting, stereolithography apparatus, 3D printing.

## I. INTRODUCTION

The exponential growth in data rates driven by emerging applications, such as device-to-device communication and massive IoT deployments, poses a prominent challenge for future 5G/6G wireless connectivity [1]. Consequently, modern RF antenna communication systems must concurrently accommodate multiple standards and support modes of operation. Specifically, WG-based components are preferred due to being able to handle high power levels for these antenna networks. However, using conventional RF front-end (RFFE) design and integration techniques will result in bulky and heavy subsystems. Therefore, novel design and integration methodologies are essential to realize compact, lightweight and high performance RFFE components. In response to this need, recent advancements in AM technologies have ushered in a new era for achieving high performance 3D RF components with

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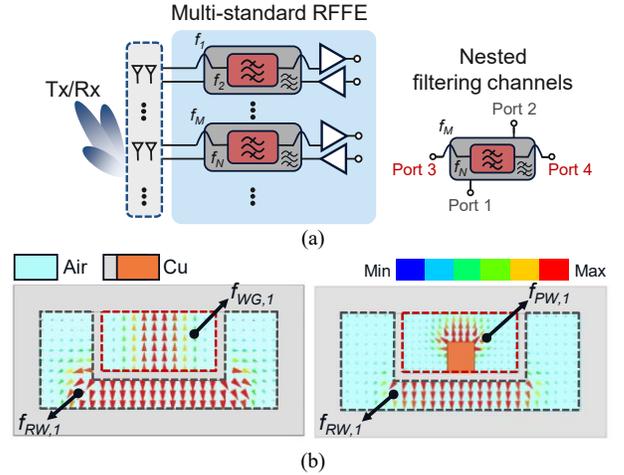


Fig. 1. (a) Proposed multi-standard RFFE implementation supporting two communication bands with a reduced number of BPFs, enabled by the proposed nested RW resonator-based filter concept. (b) Nested RW-WG and RW-PW resonator concepts. E-field distribution of the RW-WG resonator that resonates at  $f_{RW,1} = 6.75$  GHz and at  $f_{WG,1} = 15.375$  GHz (left). E-field distribution of the RW-PW resonator that resonates at  $f_{RW,1} = 6.75$  GHz and at  $f_{PW,1} = 10.0$  GHz (right).

complex geometries, such as vertically-stacked coaxial RF diplexers [2]. On the other hand, to further reduce both size and weight, a Lights-Out Digital Manufacturing (LDM) piezo drop-on-demand two material inkjet-printing process has been suggested for the realization of self-packaged 3D RF components, for example, bandpass filtering baluns [3].

In this project, by leveraging free-form capabilities of the aforementioned advanced AM integration technologies, new classes of monolithically-integrated, compact 3D waveguide RF filtering solutions are reported. The project NERON introduces a novel high-Q nested RW resonator that supports two fully isolated and independently reconfigurable fundamental modes within a single resonator and their applications to compact dual-channel BPFs. Additionally, the potential of a two-material piezo drop-on-demand inkjet printing process are proposed for the realization of 3D self-packaged, highly miniaturized, and ultra-lightweight 3D waveguide BPFs.

## II. NESTED RIDGE WAVEGUIDE DUAL-CHANNEL FILTERS

The proposed nested RW-WG and RW-post-loaded WG (RW-PW) resonators are shown in Fig. 1(b) serve as the core building blocks for highly miniaturized nested dual-channel filters used in the proposed multi-standard RFFEs, such as

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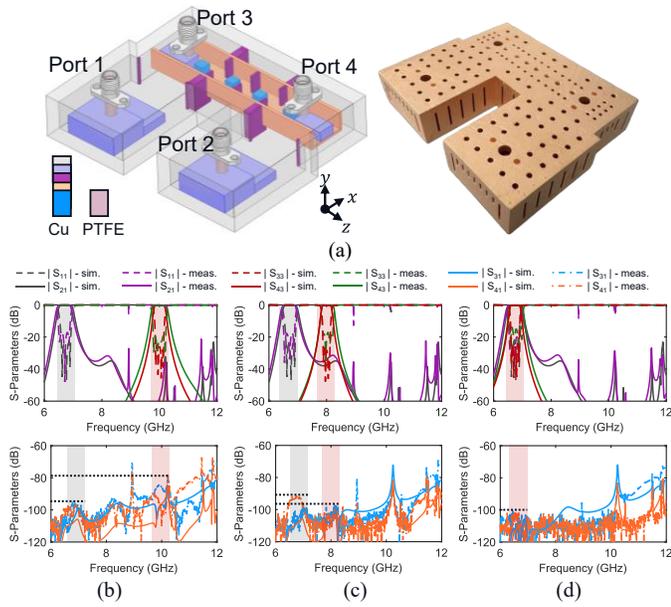


Fig. 2. Nested RW-PW resonator-based dual-channel BPF comprising one 3<sup>rd</sup> order LFFC and one 4<sup>th</sup> order HFFC. (a) 3D EM-simulated model (left). Manufactured prototype (right). RF-measured and EM-simulated S-parameters of the dual-channel RW-PW-based higher-order BPFs for (b) widely-spaced channels ( $AFR = 1.5$ ), (c) closely-spaced channels ( $AFR = 1.2$ ), and (d) co-located channels ( $AFR = 1.0$ ).

those shown in Fig. 1(a). The traditionally unused area of a RW is exploited to create an additional channel allowing for an additional fundamental mode to be excited at a frequency  $f_{WG,1}$  (for RW-PW, at a frequency  $f_{PW,1}$ ) while the fundamental mode of the RW resonator will be at a frequency  $f_{RW,1}$ . The detailed mode characteristics have been discussed in [4]. To demonstrate the potential of the proposed nested RW-WG and RW-PW resonator for the realization of dual-channel filter architectures, the 3D EM-simulated structure of the proposed dual-channel BPF is shown in Fig. 2(a), together with the manufactured prototype. Port 1–Port 2 is referred to as the low-frequency filtering channel (LFFC), and Port 3–Port 4 is referred to as the high-frequency filtering channel (HFFC). To determine possible channel allocations and their corresponding achievable frequency ratios ( $AFRs$ ), a comprehensive analysis of design procedures has been presented and published in [4] and [5]. Finally, RF-measured and EM-simulated S-parameters are provided in Fig. 2(b), (c), (d), demonstrating three different design showcases. As shown, the channel allocations are configured over a wide range of  $AFR$  values, including widely spaced, closely spaced, and co-located channels, respectively. The experimental validation exhibits ultra-low insertion loss (IL) ( $< 0.5$  dB), and exceptional inter-channel isolation (up to 116 dB), with a total structure weight of less than 80 g.

### III. MULTI-MATERIAL INKJET-PRINTED WAVEGUIDE BPFs

The advanced multi-material and multi-process capabilities of inkjet-printing technology is also explored and leveraged to realize self-packaged 3D WG filter components. Fig. 3 presents 3D EM-simulated model of the proposed inkjet-printed BPF based on folded WG resonator approach. Design details have been reported and published in [6]. A comparison

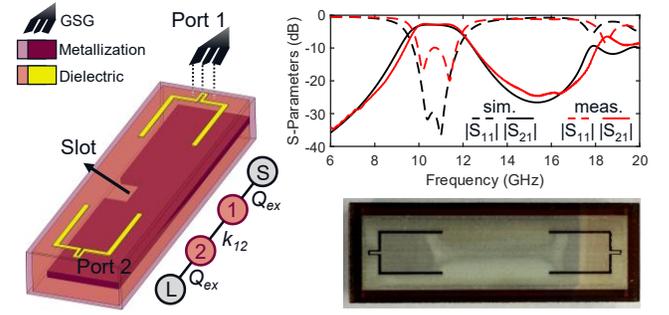


Fig. 3. Inkjet-printed folded waveguide resonator-based BPF. Bird's-eye view of the 3D EM-simulated structure and its corresponding coupling routine diagram (left). RF-measured and EM-simulated S-parameters, together with the manufactured prototype (right).

of the RF-measured and EM-simulated S-parameters is also provided in Fig. 3, including manufactured prototype. It shows a second-order transfer function with a center frequency of 10.73 GHz, min-in-band IL of 2.65 dB, and a 3 dB fractional bandwidth of 21.6%. Furthermore, the BPF exhibits a volume of  $0.34\lambda_0 \times 1.26\lambda_0 \times 0.16\lambda_0$  and only weighs 1.16 g.

### IV. CONCLUSION AND FUTURE PLANS

In this paper, 3D RF filtering solutions are presented by leveraging the recent AM technologies for upcoming 6G wireless communication systems. A novel nested RW-WG and RW-PW resonators have been proposed, providing two fully-isolated and independently reconfigurable fundamental resonances within a single resonator. Realization of dual-channel filters with passbands placed at the same frequency or closely/widely spaced frequency bands are also demonstrated for different multiplexing scenarios. Furthermore, a potential of a new AM technique based on a two-material inkjet printing process is examined and exploited for the realization of ultra-compact and lightweight 3D waveguide BPFs.

My ultimate career goal is to become a professor, where I can contribute to the field of RF engineering and aspire to positively impact students' lives by teaching, educating, and guiding the next generation of engineers. Participating in IMS 2025 and observing the wide range of applications has motivated me to further contribute to the field of RF.

### REFERENCES

- [1] S. Zhang, J. Liu, H. Guo, M. Qi and N. Kato, "Envisioning device-to-device communications in 6G," in *IEEE Network*, vol. 34, no. 3, pp. 86-91, May/June 2020.
- [2] K. Zhao and D. Psychogiou, "Three dimensional printed vertically-stacked single-/multi-band coaxial filters and RF duplexers," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 71, no. 11, pp. 4957-4968, Nov. 2023.
- [3] J. Steele and D. Psychogiou, "Self-Packaged inkjet-printed vertically integrated Rf co-designed bandpass filtering baluns," in *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 14, no. 11, pp. 2124-2127, Nov. 2024.
- [4] B. Dogan and D. Psychogiou, "Monolithically integrated dual-channel filters using nested waveguide resonator arrays," in *IEEE Transactions on Microwave Theory and Techniques*.
- [5] B. Dogan and D. Psychogiou, "Monolithically-integrated nested ridge waveguide dual-channel filters," *2025 55th European Microwave Conference (EuMC)*, Utrecht, Netherlands, 2025, pp. 857-860.
- [6] B. Dogan and D. Psychogiou, "Ultra-compact inkjet-printed folded waveguide resonator-based bandpass filters," *2025 European Microwave Conference*, Utrecht, Netherlands, 2025, pp. 775-778.